

Quantitative feasibility study of magnetocaloric energy conversion utilizing industrial waste heat

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HIGHLIGHTS

- We model magnetic energy conversion machine for the use of industrial waste heat.
- Efficiencies and masses of the system are evaluated by a numerical model.
- Excellent potential of profitability is expected with large low-exergy heat sources.

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ABSTRACT

The main objective of this theoretical study was to investigate under which conditions a magnetic energy conversion device (MECD) – utilizing industrial waste heat – is economically feasible. Furthermore, it was evaluated if magnetic energy conversion (MCE) has the potential of being a serious concurrent to already existing conventional energy conversion technologies. Up-today the availability of magnetocaloric materials with a high Curie temperature and a high magnetocaloric effect is rather limited. Therefore, this study was mainly focused on applications with heat sources of low to medium temperature levels. Magnetic energy conversion machines, containing permanent magnets, are numerically investigated for operation conditions with different temperature levels, defined by industrial waste heat sources and environmental heat sinks, different magnetic field intensities and different frequencies of operation (number of thermodynamic cycles per unit of time).

Theoretical modeling and numerical simulations were performed in order to determine thermodynamic efficiencies and the exergy efficiencies as function of different operation conditions. From extracted data of our numerical results, approximate values of the total mass and total volume of magnetic energy conversion machines could be determined. These important results are presented dependent on the produced electric power. An economic feasibility study supplements the scientific study. It shows an excellent potential of profitability for certain machines. The most important result of this article is that the magnetic energy conversion technology can be economically and technically competitive to or even beat conventional energy conversion technologies. This is true especially in those cases when large, low-exergy heat sources are at one's disposal.

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1. Introduction

The society learns more and more about the finiteness of energy and material sources on the planet Earth, as well as of the human harmful impact on the environment. An efficient energy use and improvements of technologies positively reduce the exploitation

of sources, and thus reduce harmful impacts on the environment (see e.g. Ref. [1]). The optimization of energy utilization can be efficiently performed by the application of exergy concepts and related exergy analyses [2–4]. The latter represents a perfect tool to determine reductions of irreversibility's and the introduction of improvements in different kinds and at different levels of processes. Most important is the choice of an appropriate energy source and to efficiently operate the chosen process. It must be further evaluated if users with different kinds of energy and exergy demands can be combined in a single process. For instance, besides of power generation, the use of waste heat can be efficiently integrated into district heating networks [5] or into different industrial processes [6], including the cooling by sorption technologies [7,8].

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Nomenclature

Standard

f	frequency (Hz = s ⁻¹)
H	magnetic field strength (A m ⁻¹)
M	magnetization (A m ⁻¹)
n	real number (–)
P	power, power loss (W)
Q	heat (J)
$\dot{q}$	specific heat flux (W kg ⁻¹)
$\dot{Q}$	heat flux (W)
s	specific entropy (J kg ⁻¹ K ⁻¹)
T	temperature (K, °C)
U	internal energy (J)
V	volume (m ³)
w	specific work (J/kg)
W	work (J, N m)
ZT	thermoelectric figure of merit

Greek

μ	magnetic permeability (A ⁻¹ m ⁻¹)
η	efficiency

Indices

ad	adiabatic
admax	maximal adiabatic
ass	magnets assembly
C	cold sink
Carnot	Carnot

Curie	Curie
Eddy	eddy currents
el	electric
ext	real temperature difference
Gen	general, heat losses
Gap	fluid gap
H	hot, source
hot	hot
hyd	hydraulic for one stage
Hyd	hydraulic for n stages
Hyst	hysteresis
mag	magnets
max	maximal
mcm	magnetocaloric material
Mot	motor
multi	multistage
n	number of stages
Sc	superconducting
source	source
stage	stage
sup	superconductivity
tot	total, overall
th	thermodynamic
thmulti	thermodynamic multistage
0	external, vacuum
II	exergy

Furthermore, all the processes must be optimized and the losses minimized [9]. In newer applications an increasing number of energy conversion processes are involved to gain back energies with higher exergy potentials [10]. Most of ancient power generation technologies that utilize waste heat, are based on the Water Steam Rankine Cycle. In the last five decades, numerous new technologies became available on the systems market. For utilizing heat sources with a low exergy potential, the Organic Rankine Cycle (ORC) [11–14], and the Kalina cycle [15–17] were successfully applied. Another interesting alternative is the thermoelectric energy conversion method. This technology is interesting because of its simplicity and the lack of any moving parts. However, because of the very low efficiency, large efforts are undertaken to increase it. This is especially the case in bulk thermoelectric materials [18–22]. The thermoelectric efficiency of these devices is characterized by the Figure of Merit (ZT). Whereas the best bulk materials show ZT values slightly above one, in super lattices these can reach values of up to $ZT = 3$ (see also in Fig. 9 which efficiencies can be achieved by different ZT 's). Another well known technology is the Stirling power conversion technology. This technology may be further divided into the mechanical and the thermoacoustic part. Stirling engines are mostly applied in micro-cogeneration [23,24].

The production cost and operation efficiency of the above described existing technologies are well known. On the other hand – to the authors' best knowledge – up-today there is no existing commercially driven magnetocaloric engine (in the literature named also thermomagnetic engine). Power plants, based on the magnetic or magnetocaloric principle, are serious candidates for more efficient and economic energy conversion in the near future. Takahashi [25] and Solomon [26] have investigated magnetic systems to recreate exergy from low-level industrial waste heat processes. Takahashi dealt with a hot source of a liquid of 95 °C. An experimental tri-pole wheel machine was investigated and the main results have been published. Solomon [26] made a relevant study of a “static machine” and evaluations of the coefficient of

performance for industrial machines (20 MW of net power) with a hot source temperature up to 225 °C. A recent study, performed for the Swiss Federal Office of Energy (SFOE) [27], summarizes the present state of the conventional energy conversion technologies and makes first proposals for magnetic, respectively magnetocaloric energy conversion systems. In this study the potential of this technology is estimated, and its limits are outlined. This article mainly presents results of the study, however, it shows a focus on the utilization of industrial waste heat. Therefore, detailed information on magnetocaloric energy conversion for industrial applications is presented. The analysis performed is based on a very simple model. The reason for this kind of approach was to develop a simple and fast tool, and by avoiding too complex configurations and geometries to avoid the demand for very sophisticated models.

2. Magnetocaloric energy conversion machines

Magnetic energy conversion can actually be driven with every material showing a temperature dependent magnetization curve. A magnetic material in the alternating magnetic field shows a force that depends on the magnetization of the material. If now from an entrance to an outlet of a magnetic field region, a magnetic material is moved and its temperature is increased by heat absorption, then the force field at the entrance and the one at outlet are different. This results in a torque, which can move a slab or rotate a wheel. If such a moving object is connected to an electric generator, by simply using heat from a heat source, electricity can be gained (see e.g. [28–33]). Studying magneto-thermodynamics in general [28] and with more focus on the temperature-entropy diagram, it immediately becomes evident that the magnetocaloric effect increases the efficiency of a thermodynamic cycle of a magnetocaloric energy conversion machine. The reason is the reversibility of the processes of magnetization and demagnetiza-

tion, which in analogy with conventional systems, represents compression and expansion, respectively.

If in a magnetocaloric energy conversion machine, air or other gases (e.g. similar as in the Stirling engine) are used as heat transfer fluid, then the heat transfer rate will be too low. Without having a very large surface (porous structure), the efficiency will also be low. On the other hand, a substantial increase of the efficiency can be expected by applying the layered bed technique. Because the adiabatic temperature changes of magnetocaloric materials are limited to a certain temperature interval, efficient magnetocaloric energy conversion machines must comprise a cascade or a regenerative thermodynamic cycle. A tuning of the Curie temperature to the (steady-state) operation temperature – by using in a selective manner different materials in different sections of the magnetocaloric regenerator – is a proposed method to substantially increase the efficiency of a plant.

With the new discoveries of magnetocaloric alloys with a large magnetocaloric effect and Curie temperatures above the ambient temperature, material scientists are opening the door for a development of magnetocaloric energy conversion machines (see e.g. in Ref. [34]). Such alloys, layered in the magnetocaloric regenerator with segments having different Curie temperatures, can cover temperature spans that are required in practical applications.

At present most of the magnetocaloric materials are developed for applications in the magnetic refrigeration domain near room temperature. Magnetocaloric materials are characterized by their Curie temperature of phase transition. These should exist in the temperature interval between heat source and heat sink. And the temperature interval, in which the magnetocaloric material exhibits the magnetocaloric effect, should be as large as possible. However, most of the magnetocaloric materials show a large magnetocaloric effect in a rather narrow temperature interval. Therefore, they are not broadly applicable to any operation temperature (this is why layering with materials having different Curie temperatures is required). Since most of the research activities have been performed in magnetic refrigeration domain, the number of available magnetocaloric materials with different Curie temperatures is rather large. On the other hand, only a small number of research activities has been devoted to the application of materials in magnetic power conversion.

An extensive review of the literature on magnetocaloric materials with a phase transition above 309 K has been performed [34] (see Fig. 1). Although not all of the required magnetocaloric materials are yet available, in the considered temperature interval of interest for our purposes, one may expect that new materials will be developed in the near future.

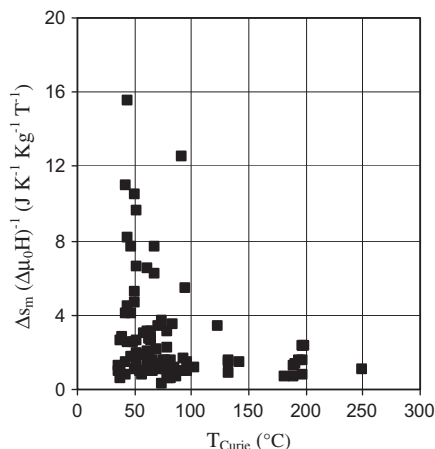


Fig. 1. The variation of the entropy per unit of magnetic field change for considered magnetocaloric materials, from Ref. [34].

The magnetocaloric energy conversion machines may be static, moving rectilinear or of rotary type. According to the knowledge of the authors, up-to-present no publication related to linear magnetic power conversion devices exists. However, few publications regard static machines, but most of them are related to rotary machines. The aim of this study is the analysis of exergy losses in industrial applications of rotary and static magnetocaloric power generators, as described in Refs. [27] and [26], respectively.

3. Theory

A magnetocaloric energy conversion engine works with the principle of a varying magnetization of the magnetocaloric material. This occurs due to the heat absorption from the heat source, which causes a temperature difference of the magnetocaloric material at the entrance and exit of the magnetic field. The first law of thermodynamics in the absence of the volume work is [28]:

$$dU = dQ - \mu_0 H_0 dM, \quad (1)$$

where dQ presents the heat added to a system, and the second term presents the magnetic work, performed for example to move the magnetocaloric material out of the magnetic field. There are different possible cycles, which are commonly used in magnetocaloric systems: the Carnot, Ericsson, Brayton and Stirling cycle. The maximal work is obtained from the reversible cycle, named Carnot cycle. Fig. 2 shows the thermodynamic Brayton cycle(s) of a thermomagnetic engine in an entropy temperature diagram. The machines operate between a heat source with temperature T_H and a cold sink of temperature T_C .

In order to obtain the maximal possible work for a given temperature span between heat source and heat sink, several layered (tuned) magnetocaloric materials lead to much better characteristics of a device than this is the case if only a single material is mounted into the machine. In order to increase the temperature span, a cascade or a regenerative cycle needs to be applied. Each of the layered material sections undergoes its own thermodynamic cycle, performed in the near vicinity of its Curie temperature. At Curie temperature, $T = T_{Curie}$, the adiabatic temperature change ΔT_{ad} and the entropy change Δs of the magnetocaloric material reach their maximums. Generally speaking, in magnetocaloric energy conversion machines, one should never apply a single magnetocaloric material, because the specific work capacity is rapidly decreasing with an offset of temperature away from the Curie point.

The maximal specific work of a single magnetocaloric material is defined as follows:

$$w_{\max} = \int_{s(T_C, \mu_0 H_0)}^{s(T_C + \Delta T_{ad}(T_C), \mu_0 H_0)} T ds - \int_{s(T_C - \Delta T_{ad}(T_C), 0)}^{s(T_C, 0)} T ds. \quad (2)$$

A larger temperature span than the one presented in Eq. (2) leads also to a larger specific work. However, any increase of the span would require regeneration or cascading.

The frequency of operation (number of thermodynamic cycles per unit of time) of the machine is in a direct relation to the periodic variation of the magnetization and demagnetization process of the magnetocaloric material. With this it is possible to define the theoretical maximal specific power:

$$p_{\max} = w_{\max} f. \quad (3)$$

For a multistage (or regenerative) machine, the maximal specific work comprises contributions of each layer with its distinct magnetocaloric material. Then the ideal maximal specific work of the energy conversion machine is:

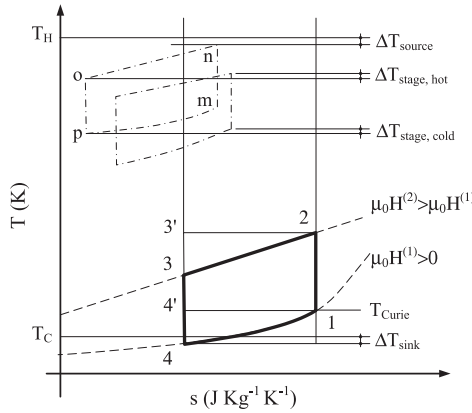


Fig. 2. Thermodynamic cycles of a thermomagnetic engine in an entropy–temperature diagram. The heat source with temperature T_H and a cold sink of temperature T_C . A Carnot cycle of the magnetocaloric heat engine is represented by the rectangle 1–2–3'–4'. In this ideal case heat rejection is an isothermal process at ambient temperature. The real operation condition of the first material layer, which undergoes a Brayton cycle, is shown by 1–2–3–4. The final operation condition of the last material layer is denoted by m–n–o–p.

$$w_{\max, \text{multi}} = w_{\max} \frac{T_H - T_C}{\Delta T_{ad}}, \quad (4)$$

where it is assumed that each layer operates only within a temperature interval with a width equal to the adiabatic temperature change. The corresponding maximal electric power of the machine is then:

$$P_{\max, \text{multi}} = w_{\max, \text{multi}} \dot{f} = P_{\text{ideal}}. \quad (5a, b)$$

4. Efficiencies

The thermodynamic efficiency of a heat engine is the ratio of the (electric) output power to the heat flux flowing into the system:

$$\eta_{th} = \frac{P_{el}}{\dot{Q}_H}. \quad (6)$$

In the ideal (Carnot) energy conversion machine the thermodynamic efficiency is defined only by the temperature levels of the heat source and heat sink:

$$\eta_{\text{Carnot}} = \frac{T_H - T_C}{T_H} = \frac{P_{\text{ideal}}}{\dot{Q}_H}. \quad (7a, b)$$

The temperature difference between the heat source and the heat sink is the maximal temperature difference, which is available for energy conversion:

$$\Delta T_{\text{tot}} = T_H - T_C. \quad (8)$$

The temperature decreases from the temperature of the heat source toward the temperature of the heat sink in multiple stages or in a regenerative cycle. Both, the cascade system of multiple stages or a regenerative process require heat transfer, which is always irreversible. This may be regarded also as a “temperature loss” during the heat transfer process between the magnetocaloric material and the working fluid. The “temperature losses” occur also due to irreversible heat transfer in the external, cold, and hot heat exchanger. The heat transfer losses are denoted as follows: one at the source ΔT_{source} , one at the sink ΔT_{sink} , and one between the material and the fluid on the cold side: $\Delta T_{\text{stage, cold}}$ and on the hot side $\Delta T_{\text{stage, hot}}$. For simplification, the temperature differ-

ence at the source and sink are assumed to be identical. This is usually the case as a design will normally show symmetric conditions. It is also assumed that the same fluid is applied in all stages.

$$\Delta T_{\text{stage}} = \Delta T_{\text{stage, cold}} = \Delta T_{\text{stage, hot}}, \quad (S9)$$

and

$$\Delta T_{\text{loss}} = \Delta T_{\text{stage, cold}} + \Delta T_{\text{stage, hot}} = 2\Delta T_{\text{stage}}. \quad (S10)$$

In Eqs. (S9) and (S10), the (S) denotes a special case. The total temperature difference between heat source and heat sink is:

$$\Delta T_{\text{tot}} = n\Delta T_{ad} + \Delta T_{\text{Source}} + \Delta T_{\text{Sink}}, \quad (11)$$

where n presents the number of stages, which may be calculated for the given temperature differences in Eq. (11). It means that the temperature difference, which is available for the magnetocaloric energy conversion, is reduced by the temperature losses in the two external heat exchangers at the sink and at the source (or explained differently, exergy is lost due to the irreversible process of heat transfer). The real temperature difference, which is finally available to perform work, is further reduced in the magnetocaloric material, because of the already mentioned internal heat transfer losses (e.g. between stages):

$$\begin{aligned} \Delta T_{\text{ext}} &= n(\Delta T_{ad} - \Delta T_{\text{stage, cold}} - \Delta T_{\text{stage, hot}}) \\ &= n \cdot (\Delta T_{ad} - 2\Delta T_{\text{stage}}). \end{aligned} \quad ((12) \text{ and } (S13))$$

From Eq. (12) one may see, that if all the internal irreversible heat transfer losses between the stages lead to a higher temperature difference than the adiabatic temperature change, no work can be performed (since all the exergy is lost). The efficiency of a multistage machine is defined as:

$$\eta_{\text{thmulti}} = \frac{\Delta T_{\text{ext}}}{T_H}. \quad (14)$$

The exergy efficiency of heat transfer processes may be expressed as the ratio between two efficiencies:

$$\begin{aligned} \eta_{\text{Multi}} &= \frac{\eta_{\text{thmulti}}}{\eta_{\text{Carnot}}} = \frac{P_{\text{ideal}} - P_{\text{thmulti}}}{P_{\text{ideal}}} \\ &= \frac{n(\Delta T_{ad} - 2\Delta T_{\text{stage}})}{T_H - T_C}. \end{aligned} \quad ((15, 16, S17))$$

where P_{thmulti} represents a power loss due to the irreversible heat transfer, where $P_{\text{thmulti}} = (1 - \eta_{\text{multi}}) P_{\text{ideal}}$. Eq. (S17) is derived by applying Eqs. (7a), (S13) and (14).

Furthermore, it is assumed that heat losses are 5% of the available exergy ($\eta_{\text{Gen}} = 0.95$, where $P_{\text{Gen}} = (1 - \eta_{\text{Gen}}) (P_{\text{ideal}} - P_{\text{thmulti}})$ represents the power lost due to the heat losses).

Mechanical work obtained by the rotation of the magnetocaloric material is partly dissipated by the eddy currents in some of the metallic parts of the energy conversion machine, and by hysteresis effect in the magnetocaloric material. The two efficiencies relating to these effects are $\eta_{\text{Eddy}} = 0.95$ (where $P_{\text{Eddy}} = (1 - \eta_{\text{Eddy}}) (P_{\text{ideal}} - P_{\text{thmulti}} - P_{\text{Gen}})$) and $\eta_{\text{Hys}} = 0.97$ (where $P_{\text{Hys}} = (1 - \eta_{\text{Hys}}) (P_{\text{ideal}} - P_{\text{thmulti}} - P_{\text{Gen}} - P_{\text{Eddy}})$).

In the Carnot cycle all the exergy input (e.g. exergy of heat) is converted into useful work. Because the electric power is obtained by an electric generator with a certain efficiency, the mechanical power to drive the generator needs to be larger. In the analysis the efficiency of the generator is estimated to be 90% of the available exergy (97% in the case of a superconducting power generator):

$$\eta_{\text{Mot}} = 0.9, \quad \eta_{\text{Mot, sup}} = 0.97. \quad (18a, b)$$

where the available exergy is represented by $P_{\text{Mot}} = (1 - \eta_{\text{Mot}}) (P_{\text{ideal}} - P_{\text{thmulti}} - P_{\text{Gen}} - P_{\text{Eddy}} - P_{\text{Hys}})$.

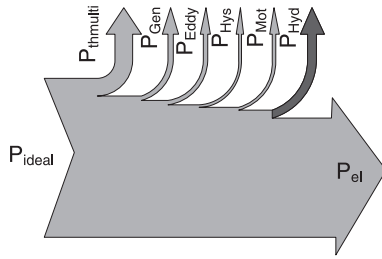


Fig. 3. Example of the exergy flow diagram with the major exergy losses (expressed as the power loss).

It is assumed that the pressure losses in all stages are identical. The loss by friction of water flow in one stage is P_{hyd} . Then for n stages it follows:

$$P_{Hyd} = nP_{hyd}. \quad (19)$$

Note, that the different size of the initial letters in the indices denotes the “specific power loss” of a single stage P_{hyd} , and in the total machine P_{Hyd} . Now it follows that:

$$\eta_{Hyd} \eta_{Carnot} = \eta_{Hyd} \frac{P_{ideal}}{\dot{Q}_H} = \frac{P_{ideal} - P_{Hyd}}{\dot{Q}_H}. \quad (20a, b)$$

Then one has:

$$\eta_{Hyd} = \frac{1}{\eta_{Carnot}} \frac{P_{ideal} - P_{Hyd}}{\dot{Q}_H} = 1 - \frac{P_{Hyd}}{P_{ideal}}. \quad (21a, b)$$

Because of its simplicity, η_{Hyd} was defined by Eq. (21a,b) and not the following relation $P_{Hyd} = (1 - \eta_{Hyd})(P_{ideal} - P_{thmulti} - P_{Gen} - P_{Eddy} - P_{Hys} - P_{Mot})$. Like this, the pressure loss contribution is a little overestimated when Eq. (22) is applied.

Fig. 3 shows the exergy flow diagram (where exergy losses are expressed by power losses $P_{thmulti}$, P_{Gen} , P_{Eddy} , P_{Hys} , P_{Mot} , P_{Hyd}).

The final thermodynamic efficiency of a machine with several stages was defined as:

$$\eta_{th} = \eta_{Carnot} \eta_{Multi} \eta_{Gen} \eta_{Eddy} \eta_{Hys} \eta_{Mot} \eta_{Hyd} \eta_{Sc}, \quad (22)$$

where the last term in the Eq. (22) only has to be taken into consideration if superconducting magnets are applied. But then additional 10% losses should be taken into account due to the high-temperature superconducting cooling system and the electric energy for magnetization. Notice, that this value for superconductivity is a very rough estimate! The theory, which has been presented, is based on the assumption that the losses of heat transfer (*Multi*) and by the friction of the water flow (*Hydr*) occur in a quasi-homogeneous manner distributed over the entire temperature range of the system. Now the exergy efficiency of the whole device is defined:

$$\eta_{II} = \frac{\eta_{th}}{\eta_{Carnot}}. \quad (23)$$

Based on this for some specific operation conditions – the total mass of magnetocaloric material is given by the following equation:

$$m_{mc} = \frac{P_{el}}{\eta_{II} \dot{W}_{max, multi}}. \quad (24)$$

Based on an extensive numerical analysis, performed by applying a finite element method for magnetic flux line calculations, the volume of the magnet assembly is approximately given by the following empirical relation:

$$V_{mag} \cong [(\mu_0 \Delta H_0)^2 - \mu_0 \Delta H_0 + 2] V_{gap}, \quad (25)$$

where the induction has to be taken in Tesla and the volumes are in cubic meter.

The mass of the magnets assembly was determined by applying a density of 7500 kg/m^3 . Other components, such as pipes, pumps, and valves, also contribute to the total mass and total volume. It was assumed that:

$$m_{ass} = 14.14 \cdot 10^{-3} P_{el} - 23.46, \quad (26)$$

where the mass is in kilogram and P_{el} in Watts. More information on the empirical Eqs. (25) and (26) can be found in Ref. [27].

5. Technical results

This analysis was based on Gadolinium and its physical properties, which follow from a mean field theory and Debye's law (see Refs. [35] and [36]). As presented in Fig. 2 each magnetocaloric material portion is assumed to undergo its Brayton thermodynamic cycle. An assumption is, that all the magnetocaloric materials, layered to perform a multi-stage process, have the same properties as Gd, but shifted to different Curie temperatures. Plain water is the working fluid (pressurized for a temperature slightly beyond 100°C).

The “temperature losses” between the stages have been assumed to be $\Delta T_{stage} = 1 \text{ K}$ and the losses at the source/sink $\Delta T_{source} = \Delta T_{sink} = 2 \text{ K}$.

In a first part of the analysis, the magnetic flux density is assumed to vary between 0 and $\mu_0 H = 1, 2$, and 10 T . The frequency of operation is chosen to be $f = 1, 2$ and 10 Hz . Notice that applications of magnetic flux densities above 2 T require the application of superconducting devices. The cold sink is water of a river with a temperature of $T_c = 12^\circ\text{C}$. The hot source is considered to be industrial waste heat with temperature levels of 45°C and 80°C , respectively. Fig. 4 shows different scenarios and the impact on the masses of components and efficiencies (thermodynamic and exergetic). This is done by considering the change of the above presented parameters and for an electrical output of 100 kW .

In the second step of the study, another source has been considered: the industrial waste heat from an indirect vapor system with a temperature of $T_H = 150^\circ\text{C}$ (condensed steam). Realistic design parameters of the machine have been chosen, i.e. the frequency of operation of $f = 2 \text{ Hz}$, and the variation of the magnetic field (given as a magnetic field induction) $\mu_0 \Delta H = 2 \text{ T}$. Quantitative values of performance of such machines are presented in Fig. 5. Corresponding mass and electric power are graphically presented in Fig. 6.

As shown in Fig. 7, the thermodynamic efficiency is 15.7% (sectors G/I). With a decrease of the number of stages, or/and introducing regenerative cycles, leads to much better results. For example, in a power plant with only four stages, 26.4% can be transferred from heat losses (Fig. 8, sector D) to electricity (G).

Different alternative technologies exist for a potential utilization of waste heat. From those, the most interesting are Stirling Power Generators (including thermoacoustic devices), Organic Rankine Cycle (ORC) Power Generators, Kalina cycle power generators and Thermoelectric Power Generators.

Fig. 9 shows a comparison of exergy efficiencies for different kinds of power generation technologies [27]. Despite the comparison is of illustrative nature (when evaluating the exergy efficiencies data was taken from different sources, where different losses were taken into consideration), it shows the high potential of the magnetocaloric system. When considering a temperature sink around ambient temperature, the exergy efficiency of the Binary ORC power generator [11,12,14,39], and the thermoacoustic Stirling power generator [23,24,40], are lower than the one obtained for a magnetocaloric system with a change of magnetic field strength of $\mu_0 \Delta H = 2 \text{ T}$. Only thermoelectric power production with thermoelectric figure of merit ZT (which was theoretically

		m_{magnet}	m_{mcm}	m_{tot}	η_{th}	η_{II}
T_H 45°C 80°C	$\mu_0 H$					
	1.0 T					
	2.0 T					
	10 T					
	f					
	2 Hz	10958	1751	14081	3.04	29.3
	5 Hz	4926	778	7096	2.79	26.9
	10 Hz	3479	550	5420	1.91	18.4
	2 Hz	7987	631	10009	4.56	43.9
	5 Hz	3411	269	5072	4.43	42.7
	10 Hz	1829	144	3365	3.98	38.4
	2 Hz	/	163	/	6.12	59.0
	5 Hz	/	68	/	6.10	58.8
	10 Hz	/	33	/	6.03	58.1
	2 Hz	4928	779	7098	6.08	31.6
	5 Hz	2259	357	4007	5.49	28.5
	10 Hz	1538	243	3173	3.9	22.2
	2 Hz	3610	285	5286	9.08	47.2
	5 Hz	1552	123	3066	8.78	45.6
	10 Hz	824	65	2280	7.96	41.3
	2 Hz	/	74	/	12.17	63.2
	5 Hz	/	31	/	12.12	62.9
	10 Hz	/	15	/	11.99	62.2

Fig. 4. Example of the magnetocaloric energy conversion system with a cold source of $T_C = 12^\circ\text{C}$ is shown. Approximate values for mass (in kg) were calculated for the generated electric power of 100 kW. Masses were calculated by the application of numerical results from the finite element simulations and their evaluation on magnet assemblies. Eighteen different cases for mass are presented in the list on the right-hand side. Further information can be found in Ref. [34].

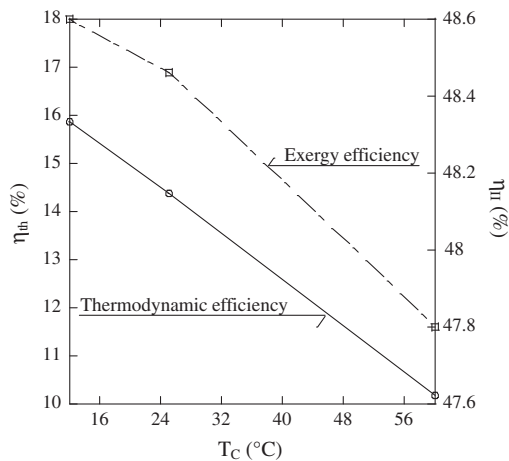


Fig. 5. Presentation of the exergy and thermodynamic efficiency of the magnetocaloric energy conversion machine. The available thermal power is defined by a mass flow of water of 0.417 kg s^{-1} , the hot source with temperature $T_H = 150^\circ\text{C}$, and the variable cold sink at temperature T_C . The frequency of operation is in all cases $f = 2 \text{ Hz}$. The change of magnetic field strength is $\mu_0 \Delta H = 2 \text{ T}$.

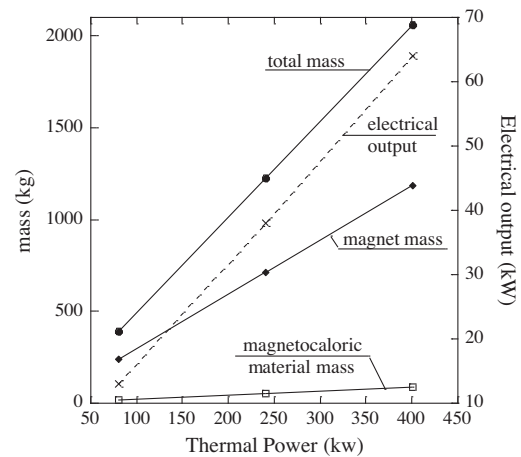


Fig. 6. The electrical output as a function of the thermal heat absorption is shown in this figure. The heat source is at the temperature $T_H = 150^\circ\text{C}$ and a cold sink at $T_C = 12^\circ\text{C}$. The frequency of operation is $f = 2 \text{ Hz}$, and the change of the magnetic field is $\mu_0 \Delta H = 2 \text{ T}$. The thermodynamic efficiency is $\eta_{\text{th}} = 0.159$ and the exergy efficiency is $\eta_{\text{II}} = 0.486$.

evaluated from [38], but may also be seen in [18,21,22]), higher than 5, could beat the exergy efficiency of a magnetocaloric conversion system considering heat sources of temperatures below $T_H = 350^\circ\text{C}$. Despite significant advances have been made over the last 10 years with new thermoelectric materials being developed, a ZT of 5 has not been reached up-to-present.

6. Economic feasibility

The cost³ of the installation comprises:

- The estimated cost of the magnetocaloric motor is expressed in CHF/kg and adjusted for trade margins (i.e. Magnetocaloric alloys: 100 CHF/kg; Magnets: 140 CHF/kg; Pre-formed steel elements: 10 CHF/kg).

- The cost of the equipment available on the market for the multiplier and the electric generator.

The detailed description of the investment cost is given in Ref. [37]. Revenue has been estimated, by taking into consideration the electric power, annual consumption, cost of maintenance, and the price of electricity. The price for production of electricity can vary from CHF 0.04/kW h for a nuclear power plant, to CHF 1/kW h for a solar energy production system. The mean production cost is CHF 0.08/kW h and 0.10/kW h, to which are added the cost of transport, and the margin, to reach the final price of electricity. We have assumed and considered a final price of electricity between CHF 0.05/kW h and 0.20/kW h, depending on the typology of the market.

With these elements, the profitability of a magnetocaloric motor was calculated with standard economic analysis tools, such

³ Considered exchange rate (01.08.2009): 1 CHF = 0.657 Euro = 0.937 USD.

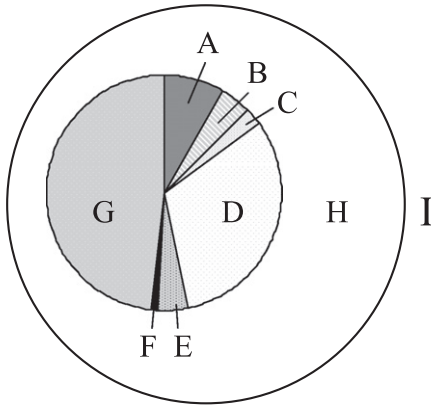


Fig. 7. Areal presentation of the exergy losses (A = motor, B = Eddy current, C = Hysteresis, D = multi, E = Generator, F = water friction), the useful exergy (G), the anergy (H) and the full energy in the system are shown above. The investigated system is a magnetocaloric energy conversion machine operating between a hot source at temperature $T_H = 150^\circ\text{C}$ and a cold sink at $T_C = 12^\circ\text{C}$. The available thermal power is 241 kW. The frequency of operation is $f = 2$ Hz and the change of magnetic field strength $\mu_0\Delta H = 2$ T.

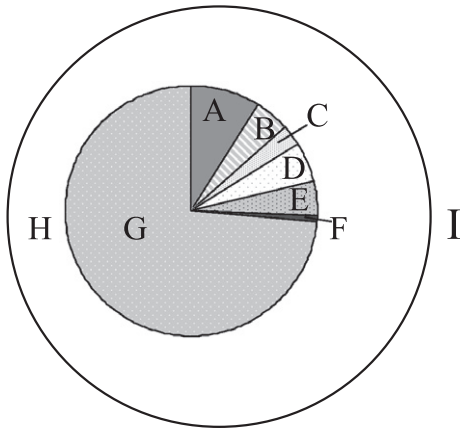


Fig. 8. The decrease of exergy losses with the reduction of the number n of stages of regenerative cycles are shown in this figure. All other parameters are the same as fixed in the investigation leading to the results shown in Fig. 6. Introducing regenerative heat transfer leads to a substantial improvement. The relative exergy efficiency increases from 48.1% up to 73.5%. The distribution of different (exergy) losses (A–F), the useful exergy G and the anergy H are also shown in this “pie diagram”.

Table 1

Three different scenarios have been considered and evaluated.

Characteristics	Units	Case 1	Case 2	Case 3
Hot source temperature	$^\circ\text{C}$	80	150	80
Cold source temperature	$^\circ\text{C}$	12	12	12
Available waste heat	MW	1.5	0.24	15
Electric output power	kW e	100	38	1000
Magnetic field difference	T	2	2	1
Frequency	Hz	6	5	6
Hours of use	Hours/year	4000	3520	8320
Produced electricity	kW h/year	400,000	134,000	8,320,000
For CHF 0.10/kW h				
– Pay back	Year	21.9	8.3	4.9
– Net current value*	CHF	–441,000	–23,000	958,000
– Internal rate of return*	%	–12.2	3.6	15.7
For CHF 0.20/kW h				
– Pay back	Year	9	3.6	2.4
– Net current value*	CHF	–195,000	63,000	6,070,000
– Internal rate of return*	%	1.9	24.4	41.6

* For 10 years.

are the payback, the net current value, and the internal rate of return. In order to analyze each situation, the following values were used: The payback period must be 3–5 years maximum; after 10 years, the net current value must be between 10% and 15%, and the internal rate of return must be at least 10%. Naturally, every company applies its own specific rates, which can differ from those chosen by other companies.

The three following cases were chosen: an instant coffee factory, plants using 3 tons/h steam boilers for direct industrial use and a waste incineration plant of 15 MW. The lifetime for each of considered systems was taken to be 10 years.

The first case concerns the heat recovery of energy, dissipated by the cooling tower in a coffee preparation factory, by using a magnetocaloric machine installed between the factory's thermal discharge and the cooling tower. Characteristics are presented in Table 1. At present, the machine described above, costing approximately CHF 613,000, would not be profitable, if the price of electricity is between CHF 0.10/kW h and CHF 0.20/kW h.

Another example is the case of a magnetocaloric generator, coupled to a steam boiler condenser, with a capacity of 3 tons/h (characteristics are resumed in Table 1). The Swiss Technical Inspection Association (ASIT) estimates the present number of such steam boiler installations to be 800 for Switzerland, 3200 for France and 4000 for Germany. Based on a lifetime of 20 years, 400 of them

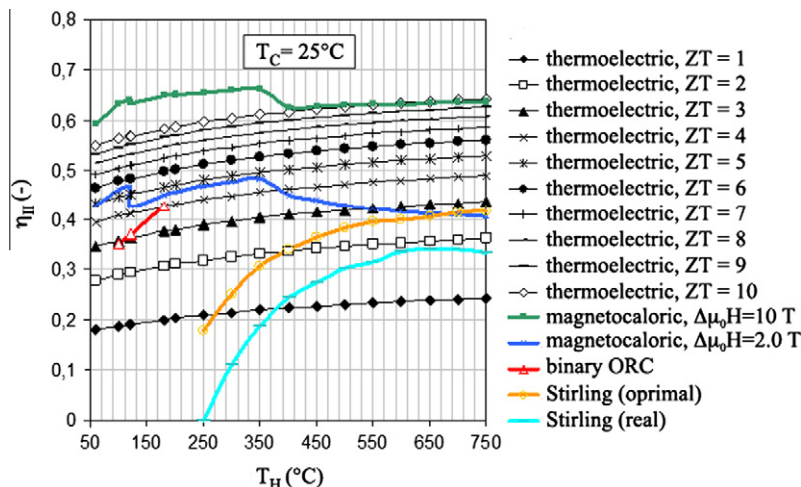


Fig. 9. Comparison of different technologies for the power production (Thermoelectric power for $ZT = 1$ –10, Magnetic power generation for 30% vol. fraction at 2 T and 10 T magnetic flux density, binary ORC power generator and thermoacoustic Stirling power generator.) (From [27]).

are changed each year in these three countries. The machine, costing approximately CHF 91,000, is under the above given configuration profitable, when the price of electricity is between CHF 0.10/kW h and CHF 0.20/kW h. This regards the conditions, when the generator operates 95% of the time, i.e. 8320 h/year. At a price of electricity CHF 0.20/kW h, the generator would still be profitable, if it operates 40% of the time, i.e. 3520 h/year. Other analyzed examples were not considered profitable with the present conditions.

The third example is the magnetocaloric machine coupled to a district heating network, and connected to a waste incineration plant (with the characteristics shown in Table 1). Such machine costs approximately CHF 3,700,000, and is profitable for the electricity price between 0.10 and 0.15 CHF/kW h. It is not profitable at the price of electricity of 0.05 CHF/kW h (Pay back: 10.8 years; net current value after 10 years: –1,599,000 CHF; Internal rate of return: –1.4%). This is at present the price of the electricity (ex-plant) of from the nuclear power plant.

A conclusion is, that at a reasonable price for electricity between 0.10 and 0.20 CHF/kW h, the magnetocaloric machine is profitable, when it benefits from inherent economies of scale.

7. Conclusions and outlook

Utilization of waste heat shows a large potential in numerous different industrial plants. For conventional systems, an efficient conversion of heat into electricity is still a matter of active research and development. This article presents a new technology, namely magnetocaloric energy conversion. It is shown that this alternative technology may be a serious candidate for the energy conversion in the near future. Based on a theoretical study, thermodynamic and exergy efficiencies were evaluated. Approximate mass and volume for such devices were defined, as the basis for a further economic analysis.

Different scenarios have been evaluated, based on different assumptions and parameters. It is shown that the mass of the device, therefore the initial investment cost, can be drastically reduced with the increase of the frequency of operation, and/or the difference of the applied magnetic field strength. The increase of the difference of the magnetic field strength positively influences the efficiency. However, an increased frequency of operation (required to increase the power density of a device) will decrease the efficiency. The reduction of the available exergy strongly depends on the number of stages of the system (i.e. heat transfer irreversibilities).

The economic analysis was performed for three selected configurations of waste heat utilization (a coffee preparation factory, a steam boiler condenser, and a waste incineration plant, respectively). The payback period, the net current value, and the internal rate of return of 10 years have been evaluated with the variation of the price of electricity, as parameter.

The results reveal a high potential of profitability for certain machines. This is especially the case when an extended annual operation time is considered.

A conclusion can be made that the magnetocaloric energy conversion technology has a good potential for market applications. However, only the realization of a prototype can prove and enable the validation of concepts and analyses presented in this study. For real engineering applications it is important to first focus on the development of new magnetocaloric materials, which can be applied in a certain temperature interval above the ambient temperature. Namely, most of the useful magnetocaloric materials are available for temperatures up to e.g. 100 °C, whereas for higher temperatures, new magnetocaloric materials need to be discovered and developed (see also Fig. 1). It is therefore expected that the

earlier magnetocaloric energy conversion devices will not be applied for high temperatures, but rather for heat sources with low exergy. This perfectly matches some renewable energy sources (e.g. geothermal and in some cases solar), as well as the utilization of (industrial) waste heat.

A very important issue is to find a better way for processing magnetocaloric materials. These have to be manufactured in very fine, ordered structures. Thanks to rapid developments in magnetic refrigeration and magnetic heat pumping, the processing, as well as other important issues (fluid switching (or valve) systems, optimized drive systems, etc.) will be solved in the near future.

The early market applications will certainly require substantial improvements of the existing know-how. Besides of the engineering problems, the development of market applications strongly depends on the financial sources, available for research and development. Despite of the proved high potential, the financial sources to support the technology are rather low compared to many other alternative technologies. Based on the existing support worldwide, one may expect that the first magnetocaloric energy conversion devices may be market available in the period of the coming 15 years.

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